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REVIEW ARTICLE

Heat and moisture exchangers and breathing system filters: their use in anaesthesia and intensive care. Part 1 – history, principles and efficiency

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Summary

Heat and moisture exchangers and breathing system filters are intended to replace the normal warming, humidifying and filtering functions of the upper airways when these structures are bypassed during anaesthesia and intensive care. Guidance on their use continues to evolve. The aim of this part of the review is to describe the principles of their action and efficiency and to summarise the findings from clinical and laboratory studies. Based on previous studies, an appropriate minimum target for moisture output is 30 and 20 $g.m^{-3}$ for long-duration use in intensive care and short-duration use in anaesthesia, respectively. The practice of reusing a breathing system in anaesthesia, provided it is protected by a filter, assumes that the filter is effective. However, there is wide variation in the gas-borne filtration performance, and contaminated condensate can potentially pass through some filters under typical pressures encountered during mechanical ventilation.

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When a patient's trachea is intubated or a supraglottic airway device is placed in situ, the normal warming, humidifying and filtering functions of the upper airways are bypassed. Hence, gas delivered to the patient needs to be artificially conditioned to replace these lost functions [1]. Heat and moisture exchangers (HMEs) are intended to conserve a portion of the patient's exhaled heat and moisture, and condition inspired gas by warming and humidifying it [2]. Breathing system filters are intended to reduce the transmission of microbes and other particulate matter in breathing systems [3].

Five types of device are available [1]. These are:

- heat and moisture exchanger with no filter (HME)
- electrostatic filter only
- pleated filter only
- electrostatic filter with HME
- pleated filter with HME.

Devices that contain both a filter and an HME are termed heat- and moisture-exchanging filters (HMEFs). The terms 'electrostatic' and 'pleated' used to distinguish the two common types of filter are not ideal, as both types rely to some extent on electrostatic charge to hold particles within the filter material and both types of material could be pleated. The main difference between the two types is the density of the fibres. For 'electrostatic' filter material, the density of fibres is comparatively low and the electrostatic charge on the fibres (either fibrillated or triboelectric-charged [1]) is high. For 'pleated' filters, the density of the fibres is high: this causes an increase in the resistance to gas flow; pleating the material increases the surface area and thus reduces resistance. This type of filter is also termed 'hydrophobic' (as the surface of the filter material repels water) or 'mechanical'. For this review, the terms 'electrostatic' and 'pleated' will be used to distinguish the two types of filter.

Heat and moisture exchangers

Historical development

Heat and moisture exchangers became available in the 1950s after the introduction of tracheostomy for facilitating mechanical ventilation of the lungs. In his report of the

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polio epidemic in Denmark in 1952, Lassen stated that, when using the technique of tracheostomy and positive-pressure artificial ventilation, 'a good humidifier is essential: otherwise incrustation of secretions may occur' [4]. Drägerwerk [5], Wally [6] and Koch et al. [7] all described similar devices soon after Lassen's report to provide a passive means of humidifying inspired gases, although Julius Jeffreys had described a similar device in 1842 [8]. These and further developments are described in Table 1.

Levels of humidity during normal breathing

When inspired gas is warmed, humidified, and delivered to the patient, the temperature and humidity of the gas should be close to the levels found in the patient's airways during normal breathing. For example, if the patient's trachea is intubated, the gas delivered at the end of the tracheal tube should have the same temperature and humidity as inspired air during normal breathing at that level.

Cole measured the temperature and humidity of inspired air during normal and increased breathing (ventilation of 7–42 $l.min^{-1}$) and found the temperature and humidity in the oropharynx to be 32–34 °C with a humidity of 32 $g.m^{-3}$ [24]. In further work, he demonstrated that the temperature of air in the pharynx varied from 31 to 37 °C over a range of inspired air conditions varying from 'arctic' to 'tropical' [25]. The relative humidity was always close to 100% (the moisture content of air fully saturated with water vapour at a temperature of 31 °C is 32 $g.m^{-3}$).

Ingelstedt measured the temperature and humidity of inspired and expired air by puncturing the crico thyroid membrane and placing a sensor in the subglottic space [26]. During nasal breathing, the minimum temperature

Table 1 Historical development of heat and moisture exchangers (HMEs) and filters.

Date	Development
1842	Jeffreys described the need for, and a solution to, the problem of humidifying gases [8] and described the 'Respirator' which consisted of layers of fine metal wires encased in leather. The layers of metal wires were thermally isolated from each other to increase the temperature gradient through the device, thus increasing the moisture-conserving performance
1952	Lassen described the techniques used for artificial ventilation in patients during the polio epidemic of 1952 in Copenhagen (intubation and positive pressure manual ventilation) and noted that 'a good humidifier is essential: otherwise incrustation of secretions may occur' [4]
1953	Marshall and Spalding described the first active heated humidifier [9]
1954	Drägerwerk patented a passive heat and moisture exchanging device [5]
1956	Walley described a passive condenser humidifier intended for patients breathing through a tracheostomy tube [6] consisting of a cylinder of 'Perspex', as the insulating layer, containing a roll of silver-plated copper gauze
1960	Concerned about the introduction of airborne microbes into a ventilator used with neonates, Sykes described using a wad of cotton wool to filter gases [10]
1963	Bishop et al. described the 'Glove Box' filter intended for use on the inlet of a ventilator which contained a filter element composed of crimped glass paper with glass tissue backing. The filter could be sterilised after use [11]
1963	Mapleson et al. described the Garthur HME consisting of 10 flat circular nickel-wire gauzes, 5 cm in diameter, clamped together as a unit intended for use between the patient and a breathing system [12]. The gauzes were thermally isolated from each other. This unit was housed in an aluminium-alloy container from which it could be removed for cleaning or replacement
1967	Hellewell et al. described the use of Williams filters on the inspiratory and expiratory ports of the ventilator which consisted of glass paper sealed within a stainless steel case by silicone rubber [13]. The filter was resistant to temperatures up to 260 °C and could be sterilised with ethylene oxide, formaldehyde vapour or by autoclaving
1972	Spence and Melville described a new active heated humidifier with a heated wire to prevent condensation in the delivery tube, which became the Fisher and Paykel humidifier [14]
1973	Mitchell and Gamble described a method to ensure that filter surfaces are hydrophobic to prevent problems with an increase in resistance to gas flow of filters caused by ingress of water [15]
1976	Prototype disposable filter described by Lumley et al. and manufactured by Pall Medical [16]
1976	Disposable HME described consisting of a roll of corrugated paper contained in a plastic casing. This HME was available in two configurations: one with 15-mm connectors at each end to connect between a tracheal tube and the Y-piece of a breathing system [17], the other with a single 15-mm connector to attach to a tracheostomy tube [18]
1979	Siemens Servo 150 HME with hygroscopic salt added to improve moisture-conserving performance [19]
1984	Chalon et al. described the use of a pleated hydrophobic filter between the patient and the breathing system both to humidify and to filter gases delivered to patients during anaesthesia [20]
1987	Gallagher et al. described the use of a pleated hydrophobic filter between the patient and the breathing system both to humidify and to filter gases delivered to patients in intensive care [21]
1990	Filters are described that use electrostatic filter material and an HME layer to provide both filtration and humidification [22]
1992	A filter is described that combines both a pleated hydrophobic filter and an HME layer to provide both filtration and humidification [23]

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during inspiration and the inspired humidity level were 32.3 °C and 35 $g.m^{-3}$, respectively; during oral breathing the minimum temperature during inspiration and the inspired humidity level were 30.5 °C and 29 $g.m^{-3}$, respectively. Subsequently, Déry et al. also measured the temperature and humidity of inspired gas in anaesthetised humans and found a mean temperature and relative humidity of 30.8 °C and 85.8%, respectively, just below the carina [27], equivalent to a moisture content of 27.3 $g.m^{-3}$.

Based on these studies and other work, Chamney recommended that gas delivered to patients whose upper respiratory tracts had been bypassed should be warmed to at least 30 °C and humidified to at least 30 $g.m^{-3}$ [28].

Some HMEs and HMEFs (but not filter-only products) can provide moisture outputs of 30 $g.m^{-3}$ or more [29–34].

Hazards caused by inadequate humidity

When the upper airways are bypassed and gas with inadequate humidity is delivered directly to the trachea, damage can occur to the lining of the trachea. In particular, inadequate humidity can cause dysfunction of the mucociliary elevator, which comprises respiratory cilia lining the trachea and functions by moving fluid and mucus towards the larynx.

Williams et al. described a range of dysfunction that can occur in the respiratory tract if the humidity and temperature of the delivered gas to a patient are not optimal [35]. This was (in order of severity of dysfunction):

1 no apparent dysfunction, but inspired gas has lower temperature and humidity than body temperature and pressure saturated (BTPS) conditions (i.e. 37 °C and 44 g m^{-3})
2 thickened mucus, causing slow mucociliary transport
3 mucociliary transport stops
4 cilia stop beating
5 cell damage
6 decreased compliance and functional residual capacity of the lungs, atelectasis, and shunt.

Williams et al. used data from 17 published studies investigating the effect of different levels of humidity on the respiratory tract to establish a model of dysfunction in terms of humidity deficit (difference between the delivered humidity level and BTPS conditions). The optimum level of humidity defined by Williams et al. was BTPS conditions, so that the optimum humidity deficit was zero. However, from the model, there was no evidence that clinically significant dysfunction would occur if the humidity deficit was about −11 $g.m^{-3}$, giving a minimum acceptable inspired humidity level of about 33 $g.m^{-3}$. Furthermore, only two of the 17 studies were on humans; the remaining 15 were carried out on various species of mammals (rat, rabbit, dog, pig and guinea pig).

The first edition of the International Standard for humidifiers for medical use was published in 1988 [36]. It stated that the minimum amount of moisture necessary to prevent inspissation of secretions (thickening by dehydration) for patients whose upper airways are bypassed is 30 $g.m^{-3}$, equivalent to a humidity deficit of −14 $g.m^{-3}$. In the second (published in 1997) and third (published in 2007) editions, this was increased to 33 $g.m^{-3}$, although there was no rationale beyond stating that 'the upper airway provides 75% of the heat and moisture supplied to the alveoli' and 'the humidifier needs to supply this missing heat and moisture' [37].

Humidity requirements in anaesthesia

During anaesthesia, as compared with intensive care, the time duration of the bypass of the upper airway is much shorter. Williams et al.'s model of humidity deficit and duration of exposure on dysfunction of the respiratory tract [35] showed that lower levels of humidity could be tolerated for short periods of time without causing dysfunction. Kleemann proposed a minimum level of 20 $g.m^{-3}$ [38], sufficient to prevent damage to tracheobronchial epithelia during 10 h of mechanical ventilation.

This level of humidity can be provided during anaesthesia when a circle breathing system is used; the reaction of exhaled carbon dioxide with the carbon dioxide absorber (e.g. soda lime) generates water vapour that can adequately humidify inspired gases, particularly if low fresh gas flows are employed [38–41]. Therefore, the additional use of HMEs in this situation is probably not required. However, the use of a filter at the patient connection port, to protect the breathing system and the patient, can still reduce the moisture loss from the patient and thus increase the moisture content of gas delivered to the patient, even if the filter has a low moisture output [42].

Breathing system filters

Historical development

Filters became available to remove microbes from gases delivered to patients in the early 1960s. However, much earlier, in 1873, Skinner had objected to the principle of breathing through apparatus that others had already used [43]. In 1952, Joseph reported cases of cross-infection of follicular tonsillitis considered to have arisen from airborne spread from contaminated reservoir bags [44]. Williams et al. described the death of five patients in one ward in 1960, likely to have occurred because of air borne cross-infection with *Pseudomonas pyocyanea* [45]. Bishop et al. described a case where a patient

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developed *P. pyocyanea* and subsequently died [46]. The patient had received postoperative mechanical ventilation of the lungs. The breathing system of the ventilator was subsequently found to be grossly contaminated with the organism. Bishop then described the use of a filter placed on the air inlet port of the ventilator to prevent any microbes in the room air from being entrained and delivered to the patient (position 2 in Fig. 1) [11].

The importance of this work was highlighted by further reports of deaths arising from cross-infection. For example, Phillips and Spencer described how all eight patients receiving mechanical ventilation for acute exacerbations of chronic lung disease in one ward succumbed to *P. aeruginosa* infection, with two of the patients dying [47].

Further developments saw the introduction of filters suitable for placing at positions 3, 4 and 5 in Fig. 1. Performance has been measured by challenging filters with microbes [33, 48–52] and, following the publication of the standard for breathing system filters [3], by sodium chloride particles of the most penetrating particle size for the filter material [31, 53]. This method was based on that for testing respiratory protective devices [54]. Generally, the filtration performance of pleated filters is superior to that of electrostatic filters (Fig. 2).

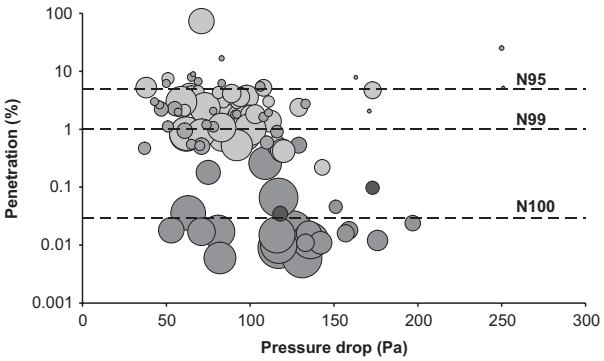

Figure 2 Penetration through filters against pressure drop. Data taken from [31]. Penetration and pressure drop were measured at 15 and 30 $l.min^{-1}$ for filters intended for use with paediatric and adult patients, respectively. Penetration (%) = 100 − filtration efficiency (%). The size of each 'bubble' is related to the internal volume of the filter. N95, N99 and N100 refer to the three classes of respiratory protective devices when challenged with sodium chloride [54]: N95, better than 95% filtration efficiency (< 5% penetration); N99, better than 99% efficiency (< 1% penetration); N100 better than 99.97% efficiency (< 0.03% penetration). ○ adult electrostatic filters; ● paediatric electrostatic filters; ● adult pleated filters; ● paediatric pleated filters. All pleated filters were at least N99, no electrostatic filters were N100, some electrostatic filters were not N95.

Effect of filters on the incidence on cross-infection

However, in 1981, two studies were published that investigated the effect of using filters on the incidence of pneumonia in patients undergoing anaesthesia [55, 56]. Garibaldi et al. [55] compared the use of a disposable breathing system used with filters attached to both the inspiratory and the expiratory ports of the absorber canister with a disposable breathing system without any filters. Although not stated, it can be assumed that each disposable breathing system was only used for one patient. Feeley et al. [56] compared the use of a sterile disposable breathing system with a filter 'placed on the proximal portion of the inspiratory limb' with a reusable rubber breathing system without a filter. In both studies, the incidence of pneumonia was similar in both filter and non-filter groups. An accompanying editorial concluded that the use of filters should be stopped until evidence became available to question the conclusions of both studies [57]. However, neither study commented on the reprocessing techniques used for the remainder of the circle system, including the absorber and ventilator or whether any contamination was found in these items. In addition, neither study addressed the issue of placing a filter at the patient connection port.

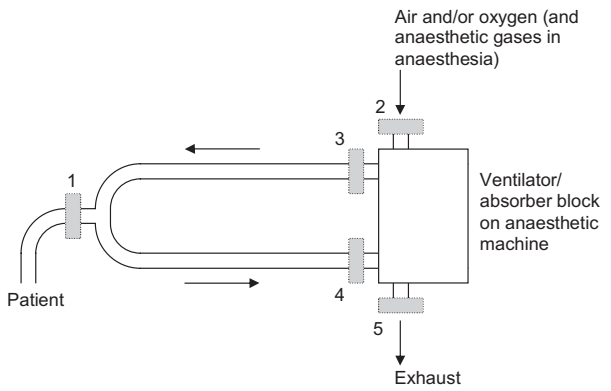

Figure 1 Possible placements of breathing system filters. 1: at patient connection port; 2: on the air inlet port; 3: on the inspiratory port; 4: on the expiratory port; 5: on the exhaust port.

This technique was first described by Chalon et al. in 1984 [20] using a filter placed between the patient and the breathing system (position 1, Fig. 1). This acted as both a filter (protecting the patient from any contamination in the breathing system and protecting the breathing system from the patient) and HME.

Three methods were then in common use: either a single-use breathing system was used for more than one patient protected by a breathing system filter; the breathing system was disposed of after each patient; or a reusable breathing system was used that was reprocessed before being used on a subsequent patient. The first method became popular in parts of Europe although not in the US [58]. However, these precautionary measures were not universally followed, and breathing systems

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without filters were used on more than one patient without reprocessing. Chant et al. described a cases series of cross-infection with hepatitis C that occurred in one surgical list in 1993 [59] when this technique was used. This strengthened the recommendations to use a filter if the breathing system was used for more than one patient without being reprocessed [60]. A second instance of a patient acquiring cross-infection with hepatitis C has also been reported [61].

The addition of a filter at the patient connection port has been shown to prevent contamination of breathing systems [62–65] and a filter does reduce the concentration of air-borne microbes when tested in vitro [33, 48–52]. However, recent work using a bioluminescence technique has demonstrated that organic soiling of the machine side of filters and breathing systems can occur during anaesthesia [66, 67]. Thus, the assumption that breathing systems remain free of microbes when a filter is used might not be appropriate. This is supported by a study in which the levels of contamination were measured in breathing systems used for more than one patient for anaesthesia over periods of 24, 48 or 72 h, with an electrostatic filter used between the patient and the breathing system; contamination was found in 5.6% of the breathing systems after 72-h use [68]. In the UK, it is common practice to use a breathing system for up to one week.

Despite being in use for nearly 50 years, there is still no evidence that the use of filters reduces the incidence of postoperative infections; in contrast, there is some evidence that the risk of acquiring lower respiratory tract infections from shared breathing systems without using filters is very low. Van Hassel et al. reported the rates of lower respiratory tract infection for patients following general or regional anaesthesia where the breathing system was cleaned daily and pasteurised in a washing machine, and a filter was only used for patients with suspected or overt respiratory infections and infections with *Mycobacterium tuberculosis* and human immunodeficiency virus [69]. Each clean and pasteurised breathing system was used for between three and seven patients. Following 9 years of surveillance of 53 800 patients, the lower respiratory tract infections rates following general or regional anaesthesia were only 0.1 and 0.2%, respectively, using this procedure, and the patients were not clustered.

However, for this large observational study, two techniques of delivering anaesthesia were used: a semi-closed system and an open system. Gas flows used were 3 and 6–9 $l.min^{-1}$, respectively. Therefore, a low fresh gas flow technique was not used. When such a technique is used, the introduction of a low flow of dry fresh gas into the breathing system is not sufficient to prevent condensation occurring. Water is generated from the reaction of exhaled carbon dioxide and carbon dioxide absorbent. Condensation poses another hazard to the patient, particularly if it is contaminated.

Liquid-borne transmission of microbes

The authors of the case report of cross-infection with hepatitis C suggested that cross-infection occurred as the patient expectorated sputum contaminated with hepatitis C virus into the breathing system, which then acted as reservoir of infection for the remaining patients on the list [59]. Filters should therefore prevent the passage of liquid (sputum in this case) from the patient to the breathing system [60]. In turn, if any contamination does get into the breathing system and condensation is present, manoeuvring the breathing system during the procedure could cause the contaminated liquid to pass into the filter. If there is sufficient volume of liquid to cover the surface of the filter on the machine side (which would depend on the orientation of the filter material [70]), then it would present an obstruction to delivery of the next breath by the ventilator. As the ventilator attempted to deliver the breath, the pressure in the breathing system would rise to the limit set on the ventilator and an alarm would be generated, alerting the anaesthetist that a blockage had occurred. Typically, the pressure limit set in the ventilator would be 30–40 cmH_2O. Therefore, the filter should be able to withstand the application of that level of pressure without allowing the passage of liquid. To allow a margin of safety, recent guidance published by the German Society of Hospital Hygiene and the German Society for Anaesthesiology and Intensive Care recommends the use of filters that can withstand a pressure of 60 hectopascals (approximately 60 cmH_2O) or 20 hectopascals above the selected maximum ventilation pressure in the breathing system [71].

The pressure required to force liquid through electrostatic filters is lower than this level [49–51, 70, 72, 73]. Any microbes contained in the liquid will also pass through the filter [49–51, 73], potentially causing contamination and cross-infection. In contrast, pleated filters generally prevent the passage of water, and any microbes it might contain, at pressures up to and above this level.

Therefore, for circle breathing systems where low fresh gas flow techniques are used, the use of electrostatic filters cannot be recommended as there is a risk of transmission of contaminated liquid from the breathing system directly into the patient's airway.

In contrast, in intensive care, the use of HMEs and filters at position 1 (Fig. 1) keeps the breathing system dry. This is important as ventilator circuits are rapidly colonised by bacteria: Craven et al. demonstrated that 33% of circuits were colonised after 2 h, 67% after 12 h and 80% after 24 h [74]. Contaminated condensate in

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ventilator circuits is a known risk factor for cross-infection and development of pneumonia [75].

A proposal for positions where the various types of device can be used in breathing systems is given in Table 2.

Humidification performance of HMEs and filters in intensive care

For long-term mechanical ventilation where the upper airways are bypassed, the minimum level of humidity required is about 30 $g.m^{-3}$ to avoid inspissation of secretions [28, 36]. The importance of choosing an appropriate method of humidification was demonstrated when filters first started being used as the sole means of humidifying inspired gases. Gallagher et al. claimed that a particular breathing system filter, the Pall BB50T, could be used as the sole method of humidification in patients receiving long-term ventilation after conducting a study on 28 patients receiving mechanical ventilation for up to 22 days [21]. However, in a comment on this study, Turner and Wright reported a patient in whom the tracheal tube had become partially blocked with dried secretions when this filter was used as the sole means of humidification [76]. Furthermore, in a case series of 170 patients for whom humidification was again provided solely by this filter, the tracheal tube of 15 patients became occluded with secretions [77]. The next 81 patients received humidification from a heated humidifier and only one tracheal tube occlusion occurred. It was noted that most tracheal tube occlusions occurred in patients who received ventilation greater than 10 $l.min^{-1}$.

Table 2 Suitable placements of different types of device.

Position (Fig. 1)	HME only	Electrostatic filter only	Pleated filter only	Electrostatic filter + HME*	Pleated filter + HME
Anaesthesia					
1	✓†		✓		✓‡
3			✓		
4			✓		
Intensive care					
1	✓			✓	✓
2		✓	✓		
3		✓	✓		
4		✓§	✓		
5		✓§	✓		

HME, heat and moisture exchangers.
*Electrostatic filters with HMEs can be used for open breathing systems used in anaesthesia. However, the assumption is that circle systems are used, which could contain condensation.
†Provided the breathing system is changed for each patient. Only required if low fresh gas flow circle anaesthesia is not used.
‡An HME is required only if low fresh gas flow circle anaesthesia is not used.
§Provided that an HME is used at position 1, so that the breathing system remains dry.

However, conclusions from this study are weak, particularly as it was not a controlled trial in which patients had been randomly assigned/allocated [78].

Martin et al. compared the Pall filter with a heated humidifier, but the study was terminated earlier than planned as a patient in the Pall filter group died because a tracheal tube became completely occluded by secretions [79]. Misset et al. also compared the Pall filter with a heated humidifier in a randomised controlled trial, and reported a higher incidence of tracheal tube occlusion in the filter group though this was not statistically significant (4 (13%) vs 2 (8%)) [80]; however, a similar study by Roustan et al. found the incidence of tracheal tube obstruction to be significantly greater in the filter group than in the humidifier group (9/55 vs 0/61): three out of the nine obstructions caused total occlusion leading to acute asphyxia [81]. Sottiaux, commenting on the study by Misset et al., also stopped a study comparing the Pall filter with the other filters earlier than planned after several tracheal tubes occluded in the Pall filter group [82]. Only two tracheal tube occlusions occurred in the study by Sidhu et al. [83] when 35 patients received humidification from the Pall filter for more than 10 days; however, in this study, regular (at least 4-hourly) instillation of saline and tracheal aspiration were performed and saline was nebulised if secretions appeared tenacious. Villafane et al. compared the reduction in the luminal diameter of tracheal tubes attributable to secretions in patients receiving humidification from three different devices: the Pall filter; the DAR Hygrobac; and a Fisher and Paykel humidifier [84]. Four complete obstructions occurred, three in patients with the Pall filter and one with the Fisher and Paykel humidifier.

The moisture output of this particular Pall filter (other devices are available from Pall with greater moisture outputs) has been measured in vitro by many groups: the moisture outputs were 21.1, 21.2 and 20.9 $g.m^{-3}$, respectively, in three studies at a tidal volume of 1.0 l [32, 34, 85]. Mebius also measured the performance of this device and stated a value of about 54% efficiency (read from a graph) at 34 °C [33]. He assumed a moisture content of 37.5 $g.m^{-3}$ for air fully saturated with water vapour at 34 °C. This implies that the moisture output was $0.54 \times 37.5 = 20.25$ $g.m^{-3}$, in good agreement with the other studies. There was a greater risk of tracheal tube occlusion from secretions when higher levels of ventilation were used [77, 79]. At lower tidal volumes, the moisture output of the Pall filter is greater. For example, the Medical Devices Directorate measured a moisture output of 26.5 $g.m^{-3}$ at a tidal volume of 0.5 l for this particular device [85]. This is common to all devices tested, although the decrease in moisture output as tidal volume increases is more marked for some devices than others.

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However, increased tidal volume ventilation is now rarely practised in intensive care, and thus the reduction in moisture output of HMEs and filters as tidal volume is increased is perhaps no longer so relevant.

Moreover, subsequent studies comparing the performance of HMEs and filters with heated humidifiers, where the HMEs or filters had a moisture output measured in vitro of more than 30 $g.m^{-3}$, have not demonstrated any increase in morbidity or mortality attributable to the use of these particular devices [86–88]. Furthermore, there is no evidence to suggest that increasing the moisture output of devices to more than 30 $g.m^{-3}$ has any beneficial effect on patient outcome.

Conclusions

The humidification requirements for patients whose upper airways are bypassed vary depending on whether the bypass occurs during anaesthesia or intensive care, as dysfunction of the mucociliary elevator depends on duration of exposure to inadequate humidity. For intensive care, a target minimum moisture output is 30 $g.m^{-3}$. For anaesthesia, an appropriate target minimum moisture output is 20 $g.m^{-3}$. Circle breathing systems using low flow techniques can provide 20 $g.m^{-3}$ water vapour. Additional use of HMEs is probably not required in this situation, although small pleated hydrophobic filters will still augment the humidity provided by the circle breathing system if they are used to protect the breathing system. Circle breathing systems can contain condensation: this liquid can pass through low-density electrostatic filters under pressures typically encountered in anaesthesia, so the use of electrostatic filters with circle breathing systems cannot be recommended.

Competing interests

This review was based on a project carried out for Covidien plc funded though a contract between Covidien and Cardiff University. AW has received conference expenses from Pall Medical, and Cardiff University has received payment from Pall Medical for AW's speaking at a meeting. AW did not gain financially from either arrangement.

References

1 Wilkes AR. Breathing filters, humidifiers and nebulizers. In: Davey AJ, Diba A, eds. *Ward's Anaesthetic Equipment*, 5th edn. London: WB Saunders, 2005: 291–303.
2 British Standards Institution. *Anaesthetic and Respiratory Equipment – Heat and Moisture Exchangers (HMEs) for Humidifying Respired Gases in Humans – Part 1: HMEs for Use with Minimum Tidal Volumes of 250 ml (BS EN ISO 9360-1:2009)*. London: British Standards Institution, 2009.
3 British Standards Institution. *Breathing System Filters for Anaesthetic and Respiratory Use – Part 1: Salt Test Method to Assess Filtration Performance (BS EN ISO 23328-1:2008)*. London: British Standards Institution, 2008.
4 Lassen HCA. A preliminary report on the 1952 epidemic of poliomyelitis in Copenhagen with special reference to the treatment of acute respiratory insufficiency. *Lancet* 1953; **i**: 37–41.
5 Drägerwerk Lübeck. *Deutsches Patentamt Patentschrift 1 169 615*. Lübeck: Drägerwerk, 27 August, 1954.
6 Walley RV. Humidifier for use with tracheotomy and positive-pressure respiration. *Lancet* 1956; **26**: 781–2.
7 Koch H, Allander C, Ingelstedt S, Toremalm NG. A method for humidifying inspired air in posttracheotomy care. *Annals of Otology, Rhinology and Laryngology* 1958; **67**: 991–1000.
8 Jeffreys J. On artificial climates for the restoration and preservation of health. *London Medical Gazette* 1842; **30**: 285–92.
9 Marshall J, Spalding JMK. Humidification in positive-pressure respiration for bulbospinal paralysis. *Lancet* 1953; **ii**: 1022–4.
10 Sykes MK. Intermittent positive pressure respiration. *Anaesthesia* 1960; **15**: 401–10.
11 Bishop C, Roper WAG, Williams SR. The use of an absolute filter to sterilize the inspiratory air during intermittent positive pressure ventilation. *British Journal of Anaesthesia* 1963; **35**: 32–4.
12 Mapleson WW, Morgan JG, Hillard EK. Assessment of condenser-humidifiers with special reference to a multiple-gauze model. *British Medical Journal* 1963; **1**: 300–5.
13 Hellewell J, Jeanes AL, Watkin RR, Gibbs FJ. The Williams bacterial filter. *Anaesthesia* 1967; **22**: 497–503.
14 Spence M, Melville AW. A new humidifier. *Anesthesiology* 1972; **36**: 89–93.
15 Mitchell NJ, Gamble DR. Evaluation of the new ''Williams'' anaesthetic filter. *British Medical Journal* 1973; **ii**: 6534.
16 Lumley J, Holdcroft A, Gaya H, Darlow HM, Adams DJ. Expiratory bacterial filters. *Lancet* 1976; **ii**: 22–3.
17 Steward DJ. A disposable condenser humidifier for use during anaesthesia. *Canadian Anaesthetists Society Journal* 1976; **23**: 191–5.
18 Walker AKY, Bethune DW. A comparative study of condenser humidifiers. *Anaesthesia* 1976; **31**: 1086–93.
19 Gedeon A, Mebius C. The hygroscopic condenser humidifier. *Anaesthesia* 1979; **34**: 1043–7.
20 Chalon J, Markham JP, Ali MM, Ramanathan S, Turndorf H. The Pall Ultipor breathing circuit filter – an efficient heat and moisture exchanger. *Anesthesia and Analgesia* 1984; **63**: 566–70.
21 Gallagher I, Strangeways JEM, Allt-Graham J. Contamination control in long-term ventilation. *Anaesthesia* 1987; **42**: 476–81.
22 Bickler PE, Sessler DI. Efficiency of airway heat and moisture exchangers in anaesthetized humans. *Anesthesia and Analgesia* 1990; **71**: 415–8.

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23 Jackson C, Webb AR. An evaluation of the heat and moisture exchange performance of four ventilator circuit filters. *Intensive Care Medicine* 1992; **18**: 264–8.
24 Cole P. Some aspects of temperature, moisture and heat relationships in the upper respiratory tract. *Journal of Laryngology* 1953; **67**: 449–56.
25 Cole P. Further observations on the conditioning of respiratory air. *Journal of Laryngology* 1953; **67**: 669–81.
26 Ingelstedt S. Studies on the conditioning of air in the respiratory tract. *Acta Oto-Laryngologica* 1956; **131**(Suppl.): 1–80.
27 Déry R, Pelletier J, Jacques A, Clavet M, Houde JJ. Humidity in Anaesthesiology III. Heat and moisture patterns in the respiratory tract during anaesthesia with the semi-closed system. *Canadian Anaesthetists Society Journal* 1967; **14**: 287–98.
28 Chamney AR. Humidification requirements and techniques. Including a review of the performance of equipment in current use. *Anaesthesia* 1969; **24**: 602–17.
29 Lucato JJ, Adams AB, Souza R, Torquato JA, Carvalho CR, Marini JJ. Evaluating humidity recovery efficiency of currently available heat and moisture exchangers: a respiratory system model study. *Clinics (Sao Paulo)* 2009; **64**: 585–90.
30 Lellouche F, Taillé S, Lefrançois F, et al. Humidification performance of 48 passive airway humidifiers: comparison with manufacturer data. *Chest* 2009; **135**: 276–86.
31 Medicines and Healthcare Products Regulatory Agency. *Breathing System Filters. An Assessment of 104 Different Breathing System Filters. Evaluation* **04005**. London: Medicines and Healthcare products Regulatory Agency, 2004.
32 Branson RD, Davis K Jr. Evaluation of 21 passive humidifiers according to the ISO 9360 standard: moisture output, dead space and flow resistance. *Respiratory Care* 1996; **41**: 736–43.
33 Mebius C. Heat and moisture exchangers with bacterial filters: a laboratory study. *Acta Anaesthesiologica Scandinavica* 1992; **36**: 572–6.
34 Eckerbom B, Lindholm C-E. Performance evaluation of six heat and moisture exchangers according to the Draft International Standard (ISO/DIS 9360). *Acta Anaesthesiologica Scandinavica* 1990; **34**: 404–9.
35 Williams R, Rankin N, Smith T, Galler D, Seakins P. Relationship between the humidity and temperature of inspired gas and the function of the airway mucosa. *Critical Care Medicine* 1996; **24**: 1920–9.
36 International Organization for Standardization. *Humidifiers for Medical Use – Safety Requirements (ISO 8185:1988)*. Geneva: International Organization for Standardization, 1988.
37 British Standards Institution. *Respiratory Tract Humidifiers for Medical Use – Particular Requirements for Respiratory Humidification Systems (BS EN ISO 8185:2007)*. London: British Standards Institution, 2007.
38 Kleemann PP. Humidity of anaesthetic gases with respect to low flow anaesthesia. *Anaesthesia and Intensive Care* 1994; **22**: 396–408.
39 Bengtson JP, Sonander H, Stenqvist O. Preservation of humidity and heat of respiratory gases during anaesthesia – a laboratory investigation. *Acta Anaesthesiologica Scandinavica* 1987; **31**: 127–31.
40 Bengtson JP, Bengtson A, Stenqvist O. The circle system as a humidifier. *British Journal of Anaesthesia* 1989; **63**: 453–7.
41 Bengtson JP, Bengtson A, Sonander H, Stenqvist O. Humidity of the Bain and circle systems reassessed. *Anesthesia and Analgesia* 1989; **69**: 83–6.
42 Wilkes AR. The moisture-conserving performance of breathing system filters in use with simulated circle anaesthesia breathing systems. *Anaesthesia* 2004; **59**: 271–7.
43 Skinner T. Anaesthesia and inhalers. *British Medical Journal* 1873; **1**: 353–4.
44 Joseph JM. Disease transmission by inefficiently sanitized anesthetizing apparatus. *Journal of the American Medical Association* 1952; **149**: 1196–8.
45 Williams R, Williams ED, Hyams DE. Cross-infection with *pseudomonas pycocyanea*. *Lancet* 1960; **1**: 376–9.
46 Bishop C, Potts MW, Molloy PJ. A method of sterilization for the Barnet respirator. *British Journal of Anaesthesia* 1962; **34**: 121–3.
47 Phillips I, Spencer G. *Pseudomonas aeruginosa* cross-infection. *Lancet* 1965; **ii**: 1325–7.
48 Holton J, Webb AR. An evaluation of the microbial retention performance of three ventilator-circuit filters. *Intensive Care Medicine* 1994; **20**: 233–7.
49 Lee MG, Ford JL, Hunt PB, Ireland DS, Swanson PW. Bacterial retention properties of heat and moisture exchange filters. *British Journal of Anaesthesia* 1992; **69**: 522–5.
50 Hedley RM, Allt-Graham J. A comparison of the filtration properties of heat and moisture exchangers. *Anaesthesia* 1992; **47**: 414–20.
51 Vandenbroucke-Grauls CMJE, Teeuw KB, Ballemans K, Lavooij C, Cornelisse PB, Verhoef J. Bacterial and viral removal efficiency, heat and moisture exchange properties of four filtration devices. *Journal of Hospital Infection* 1995; **29**: 45–56.
52 Wilkes AR, Benbough JE, Speight SE, Harmer M. The bacterial and viral filtration performance of breathing system filters. *Anaesthesia* 2000; **55**: 458–65.
53 Wilkes AR. Measuring the filtration performance of breathing system filters using sodium chloride particles. *Anaesthesia* 2002; **57**: 162–8.
54 National Institute for Occupational Safety and Health (NIOSH). *Respiratory Protective Devices. Code of Federal Regulations, Title 42, Part 84*. Morgantown, WV, USA: National Institute for Occupational Safety and Health, 1995.
55 Garibaldi RA, Britt MR, Webster C, Pace NL. Failure of bacterial filters to reduce the incidence of pneumonia after inhalation anesthesia. *Anesthesiology* 1981; **54**: 364–8.
56 Feeley TW, Hamilton WK, Xavier B, Moyers J. Sterile anesthesia breathing circuits do not prevent postoperative pulmonary infection. *Anesthesiology* 1981; **54**: 369–72.
57 Mazze RI. Bacterial air filters. *Anesthesiology* 1981; **54**: 359–60.
58 Egger Halbeis CB, Macario A, Brock-Utne JG. The reuse of anesthesia breathing systems: another difference of opinion and practice between the United States and Europe. *Journal of Clinical Anesthesia* 2008; **20**: 81–3.

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59 Chant K, Kociuba K, Munro R, et al. Investigation of possible patient-to-patient transmission of Hepatitis C in a hospital. *New South Wales Public Health Bulletin* 1994; **5**: 47–51.
60 Blood Borne Viruses Advisory Panel. *A Report Received by Council of the Association of Anaesthetists on Blood Borne Viruses and Anaesthesia: An Update (January 1996)*. London: The Association of Anaesthetists of Great Britain and Ireland, 1996.
61 Heinsen A, Bendtsen F, Fomsgaard A. A phylogenetic analysis elucidating a case of patient-to-patient transmission of hepatitis C virus during surgery. *Journal of Hospital Infection* 2000; **46**: 309–13.
62 Vézina DP, Trépanier CA, Lessard MR, Gourdeau M, Tremblay C. Anesthesia breathing circuits protected by the DAR Barrierbac S breathing filter have a low bacterial contamination rate. *Canadian Journal of Anesthesia* 2001; **48**: 748–54.
63 Vezina DP, Trépanier CA, Lessard MR, Gourdeau M, Tremblay C, Guidoin R. An *in vivo* evaluation of the mycobacterial filtration efficacy of three breathing filters used in anesthesia. *Anesthesiology* 2004; **101**: 104–9.
64 Daggan R, Zefeiridis A, Steinberg D, Larijani G, Gratz I, Goldberg ME. High-quality filtration allows reuse of anesthesia breathing circuits resulting in cost savings and reduced medical waste. *Journal of Clinical Anesthesia* 1999; **11**: 536–9.
65 Rathgeber J, Kietzmann D, Mergeryan H, Hub R, Züchner K, Kettler D. Prevention of patient bacterial contamination of anaesthesia-circle-systems: a clinical study of the contamination risk and performance of different heat and moisture exchangers with electret filter (HMEF). *European Journal of Anaesthesiology* 1997; **14**: 368–73.
66 Rees LM, Sheraton TE, Modestini C, Wilkes AR, Hall JE. Assessing the efficacy of HME filters at preventing contamination of breathing systems. *Anaesthesia* 2007; **62**: 67–71.
67 Dugani S, Kumar A, Wilkes AR. Influence of patient factors on the efficacy of breathing system filters at preventing contamination of breathing systems. *Anaesthesia* 2010; **65**: 468–72.
68 Hartmann D, Jung M, Neubert TR, Susin C, Nonnenmacher C, Mutters R. Microbiological risk of anaesthetic breathing circuits after extended use. *Acta Anaesthesiologica Scandinavica* 2008; **52**: 432–6.
69 van Hassel S, Lazeaux M, Leenders M, Kaan JA, Mintjes J. Bacterial filters in anesthesia: results of 9 years surveillance. *Infection Control and Hospital Epidemiology* 1999; **20**: 58–60.
70 Wilkes AR. The ability of breathing system filters to prevent liquid contamination of breathing systems: a laboratory study. *Anaesthesia* 2002; **57**: 33–9.
71 Kramer A, Kranabetter R, Rathgeber J, et al. Infection prevention during anaesthesia ventilation by the use of breathing system filters (BSF): joint recommendation by German Society of Hospital Hygiene (DGKH) and German Society for Anaesthesiology and Intensive Care (DGAI). *GMS Krankenhaushygiene Interdisziplinär* 2010; **5**: 1–19.
72 Cann C, Hampson MA, Wilkes AR, Hall JE. The pressure required to force liquid through breathing system filters. *Anaesthesia* 2006; **61**: 492–7.
73 Scott DHT, Fraser S, Willson P, Drummond GB, Baillie JK. Passage of pathogenic microorganisms through breathing system filters used in anaesthesia and intensive care. *Anaesthesia* 2010; **65**: 670–3.
74 Craven DE, Goularte TA, Make BJ. Contaminated condensate in mechanical ventilator circuits. *American Journal of Respiratory Disease* 1984; **129**: 625–8.
75 Gorman LJ, Sanai L, Notman AW, Grant IS, Masterson RG. Cross infection in an intensive care unit by *Klebsiella pneumoniae* from ventilator condensate. *Journal of Hospital Infection* 1993; **23**: 27–34.
76 Turner DAB, Wright EM. Efficiency of heat and moisture exchangers. *Anaesthesia* 1987; **42**: 1117–8.
77 Cohen IL, Weinberg PF, Fein A, Rowinski GS. Endotracheal tube occlusion associated with the use of heat and moisture exchangers in the intensive care unit. *Critical Care Medicine* 1988; **16**: 277–9.
78 Ippolito G. Endotracheal tube occlusion, use of heat moisture exchangers, and nosocomial pneumonia. *Critical Care Medicine* 1990; **18**: 348–9.
79 Martin C, Perrin G, Gevaudan M-J, Saux P, Gouin F. Heat and moisture exchangers and vaporizing humidifiers in the intensive care unit. *Chest* 1990; **97**: 144–9.
80 Misset B, Escudier B, Rivara D, Leclercq B, Nitenberg G. Heat and moisture exchanger vs heated humidifier during long-term mechanical ventilation. A prospective randomized study. *Chest* 1991; **100**: 160–3.
81 Roustan JP, Kienlen J, Aubus P, Aubus S, du Cailar J. Comparison of hydrophobic heat and moisture exchangers with heated humidifier during prolonged mechanical ventilation. *Intensive Care Medicine* 1992; **18**: 97–100.
82 Sottiaux T. Use of a heat and moisture exchanger during long-term mechanical ventilation. *Chest* 1992; **102**: 979.
83 Sidhu VS, Henderson SJ, Allt-Graham J. A heat and moisture exchanging filter in long-term ventilation. *Clinical Intensive Care* 1994; **5**: 289–92.
84 Villafane MC, Cinnella G, Lofaso F, et al. Gradual reduction of endotracheal tube diameter during mechanical ventilation via different humidification devices. *Anesthesiology* 1996; **85**: 1341–9.
85 Medical Devices Directorate. *Heat and Moisture Exchanger (HME). Pall BB22-15F. Evaluation* **93**. London: Medical Devices Directorate, 1991.
86 Boyer A, Thiéry G, Lasry S, et al. Long-term mechanical ventilation with hygroscopic heat and moisture exchangers used for 48 hours: a prospective clinical, hygrometric, and bacteriologic study. *Critical Care Medicine* 2003; **31**: 823–9.
87 Ricard J-D, Le Mière E, Markowicz P, et al. Efficiency and safety of mechanical ventilation with a heat and moisture exchanger changed only once a week. *American Journal of Respiratory and Critical Care Medicine* 2000; **161**: 104–9.
88 Markowicz P, Ricard JD, Dreyfuss D, et al. Safety, efficacy and cost effectiveness of mechanical ventilation with humidifying filters changed every 48 hours: a prospective, randomized study. *Critical Care Medicine* 2000; **28**: 665–71.

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